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Probing small-*x* gluons by low-mass Drell–Yan pairs at RHIC and LHC

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Abstract
We calculate the transverse momentum distribution of low-mass Drell–Yan pairs in QCD perturbation theory with all-order resummation. We demonstrate that the transverse momentum distribution of low-mass Drell–Yan pairs is an advantageous source of constraints on the gluon distribution and its nuclear dependence. With the reduction in background, we argue that low-mass Drell–Yan pairs in the forward region provide a good and clean probe of small-x gluons at RHIC and LHC.

Precise knowledge of the gluon distribution at small x is critical for reliable predictions of important p–p, p–A and A–A processes studied at the relativistic heavy-ion collider (RHIC) and at CERN's large hadron collider (LHC). Based on the data available, many models have been proposed to describe the nuclear parton distribution functions. Different models give very different predictions for the nuclear gluon distribution functions at RHIC and LHC energies [1]. The knowledge of the nuclear gluon distribution is still very poor, and we need good processes to extract the gluon distribution function. A good process to probe the gluon distribution must satisfy the following criteria: (i) it has to be reliably calculable via perturbative quantum chromodynamics (pQCD), which requires the process to be pQCD factorizable; (ii) the production cross section must be dominated by gluon-initiated sub-processes; (iii) final state medium effects must be small; and also (iv) the process should have sufficient production rate to be observed. We show in this contribution that low-mass lepton pairs produced at large transverse momentum and rapidity provide such a good probe for the nuclear gluon distribution function [2]. Drell–Yan production is also free from the complications of photon isolation that beset studies of prompt photon production [2, 3].

In the Drell–Yan process, the massive lepton pair is produced via the decay of an intermediate virtual photon, γ^*. Within the context of pQCD, the Drell–Yan cross section in a collision between hadrons A and B, $\mathrm{A}(P_\mathrm{A}) + \mathrm{B}(P_\mathrm{B}) \to \gamma^*(\to \mathrm{l}\bar{\mathrm{l}}(Q)) + X$, can be expressed in terms of the cross section for production of an unpolarized virtual photon of the same invariant mass [2],

$$\frac{d\sigma_{AB\to l^+l^-(Q)X}}{dQ^2\,dQ_T^2\,dy} = \left(\frac{\alpha_{em}}{3\pi Q^2}\right)\frac{d\sigma_{AB\to\gamma^*(Q)X}}{dQ_T^2\,dy}. \tag{1}$$

The variables Q, Q_T and y are the invariant mass, transverse momentum and rapidity of the pair. The X stands for an inclusive sum over final states that recoil against the virtual photon. An integration has been performed over the angular distribution in the lepton-pair rest frame.

Recently, it was shown that the Drell–Yan cross section at $Q \ll Q_T$ can be factorized as [4]

$$\begin{aligned}\frac{d\sigma_{AB\to\gamma^*(Q)X}}{dQ_T^2\,dy} &= \sum_{a,b}\int dx_1\phi_{a/A}(x_1,\mu)\int dx_2\phi_{b/B}(x_2,\mu)\\ &\quad\times\left\{\frac{d\hat{\sigma}^{(\mathrm{Dir})}_{ab\to\gamma^*(Q)X}}{dQ_T^2\,dy}(x_1,x_2,Q,Q_T,y;\mu_{Fr},\mu)\right.\\ &\quad+\sum_c\int\frac{dz}{z^2}\left[\frac{d\hat{\sigma}^{(\mathrm{F})}_{ab\to cX}}{dp_{T_c}^2\,dy}\left(x_1,x_2,p_c=\frac{\hat{Q}}{z};\mu_{Fr},\mu\right)\right]\\ &\quad\left.\times D_{c\to\gamma^*(Q)X}\left(z,\mu_{Fr}^2;Q^2\right)\right\}.\end{aligned} \tag{2}$$

In the above equation, $d\hat{\sigma}^{(\mathrm{F})}_{ab\to cX}\big/dp_{T_c}^2\,dy$ and $d\hat{\sigma}^{(\mathrm{Dir})}_{ab\to\gamma^*(Q)X}\big/dQ_T^2\,dy$, are perturbatively calculated short-distance hard parts. The sum $\Sigma_{a,b}$ runs over all parton flavours; $\phi_{a/A}$ and $\phi_{b/B}$ are parton distribution functions; μ is the renormalization and the factorization scale, with μ_{Fr} representing the fragmentation scale. The superscripts (Dir) and (F) indicate the direct and fragmentation contributions, respectively. The $D_{c\to\gamma^*(Q)X}$ are resummed virtual photon fragmentation functions, including all-order large $\ln^m\left(Q_T^2/Q^2\right)$ contributions in the region $Q_T^2 \gg Q^2$. The four-vector $\hat{Q}^\mu$ is defined to be Q^μ but with Q^2 set to be zero.

To demonstrate the relative size of gluon-initiated contributions, we define the ratio

$$R_g = \frac{d\sigma_{AB\to\gamma^*(Q)X}(\text{gluon-initiated})}{dQ_T^2\,dy}\bigg/\frac{d\sigma_{AB\to\gamma^*(Q)X}}{dQ_T^2\,dy}. \tag{3}$$

The numerator includes the contributions from all partonic sub-processes with at least one initial-state gluon, and the denominator includes all sub-processes. In figure 1, we show R_g as a function of Q_T at fixed y (left panel), and as a function of y at fixed Q_T (right panel) at $Q = 2$ GeV for RHIC energy. The CTEQ5M parton distribution functions are used in all our calculations with scales $\sqrt{Q_T^2 + Q^2}$. Figure 1 confirms that gluon-initiated sub-processes dominate the Drell–Yan cross section and thus low-mass Drell–Yan lepton-pair production at large transverse momentum is an excellent source of information on the gluon distribution [2]. The fall-off of R_g at very large Q_T is related to the reduction of phase space and to the fact that the cross sections are evaluated at larger values of the parton momentum fractions.

However, as seen from equation (1), there is a phase space penalty associated with the finite mass of the virtual photon, and the Drell–Yan factor $\alpha_{em}/(3\pi Q^2) < 10^{-3}/Q^2$ renders the production rates for massive lepton pairs small at large values of Q and Q_T. In order to enhance the Drell–Yan cross section while keeping the dominance of the gluon-initiated sub-processes, it is useful to study lepton pairs with low invariant mass and relatively large transverse momenta [4]. With the large transverse momentum Q_T setting the hard scale of

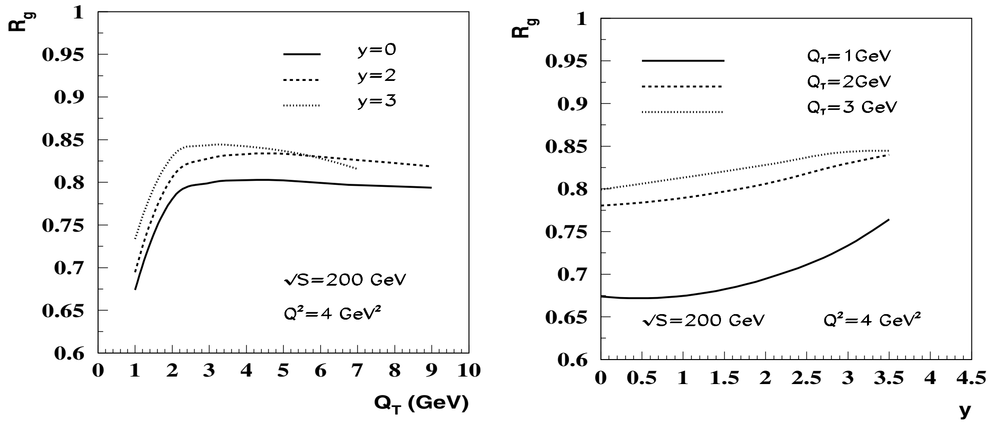

Figure 1. The ratio R_g defined in equation (3) with $Q^2 = 4$ GeV^2. Left panel: R_g as a function of Q_T for different rapidities. Right panel: R_g as a function of rapidity y for different transverse momenta.

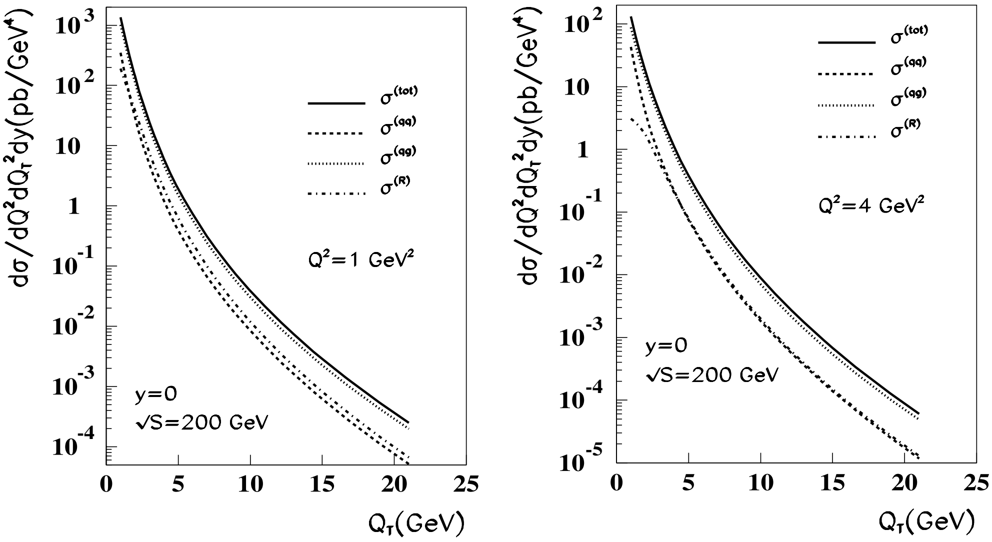

Figure 2. Drell–Yan cross section as a function of Q_T at RHIC energy $\sqrt{s} = 200$ GeV and rapidity $y = 0$, for mass $Q = 1$ GeV (left panel) and $Q = 2$ GeV (right panel). The top lines are the total cross sections; different contributions are also shown.

the collision, the invariant mass of the virtual photon Q can be small, as long as the process can be identified experimentally, and $Q \gg \Lambda_{QCD}$. For example, the cross section for Drell–Yan production was measured by the CERN UA1 Collaboration [5] for virtual photon mass $Q \in [2m_\mu, 2.5]$ GeV.

Figure 2 shows the all-order resummed result for the Drell–Yan cross section as a function of Q_T at the RHIC energy of $\sqrt{s} = 200$ GeV and rapidity $y = 0$ for two values of the mass, $Q = 1$ GeV (left panel) and $Q = 2$ GeV (right panel). The cross section increases by about a factor 10 when the Drell–Yan mass decreases from 2 GeV to 1 GeV. It might still be a challenge to measure the low-mass Drell–Yan production with the production rate shown in

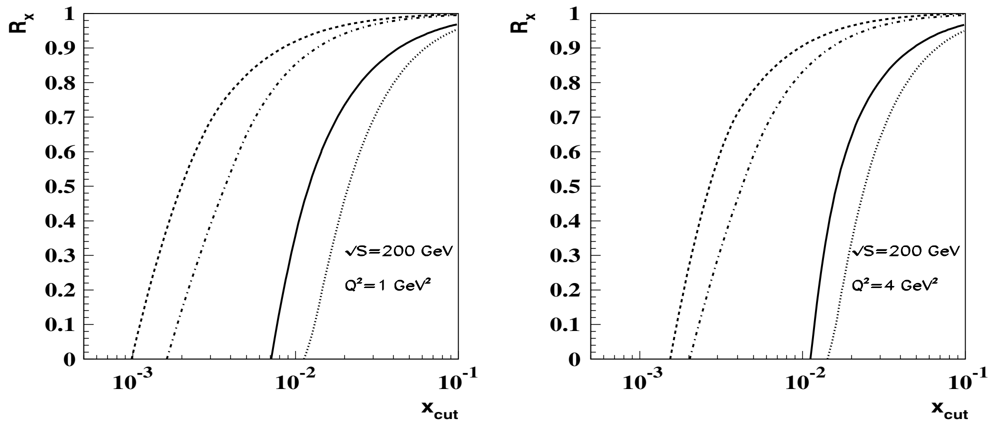

Figure 3. The ratio R_x defined in equation (4) for $Q = 1$ GeV (left panel) and $Q = 2$ GeV (right panel). Different lines in the figure are the R_x at different y and Q_{T}: $y = 0$, $Q_{\mathrm{T}} = 1$ GeV (solid); $y = 0$, $Q_{\mathrm{T}} = 2$ GeV (dotted); $y = 2$, $Q_{\mathrm{T}} = 1$ GeV (dashed); $y = 2$, $Q_{\mathrm{T}} = 2$ GeV (dot-dashed).

figure 2. At the LHC, both the collision energy and luminosity are significantly improved. Our calculation shows that the production rate at the LHC is sufficiently large for being measured.

It is very important to estimate the region of x in the gluon distribution probed by the low-mass Drell–Yan process. The x integration of the Dell–Yan cross section runs from $x_{\min}$ (given by the kinematics) to 1. We introduce a cutoff x_{cut} to limit the integration to range $x_{\min}$ to x_{cut} for the parton in the 'target' beam, and define the ratio

$$R_x = \int_{x_{\min}}^{x_{\mathrm{cut}}} \mathrm{d}x_2 \left(\frac{\mathrm{d}\sigma^{\mathrm{DY}}}{\mathrm{d}x_2}\right) \Bigg/ \int_{x_{\min}}^{1} \mathrm{d}x_2 \left(\frac{\mathrm{d}\sigma^{\mathrm{DY}}}{\mathrm{d}x_2}\right). \tag{4}$$

The shape of R_x establishes which region dominates the x integration—the region of x low-mass Drell–Yan data could provide precise information about. In figure 3 we plot R_x as a function of x_{cut} for $Q = 1$ GeV (left panel) and $Q = 2$ GeV (right panel) for different rapidities and transverse momenta Q_{T}. Figure 3 shows that in the central rapidity region $x_2 \sim [10^{-2}, 10^{-1}]$ dominates the integration for both $Q = 1$ GeV and $Q = 2$ GeV. Figure 3 also provides important information about the forward region. At $y = 2$, 90% of the cross section is given by $x_2 < 0.01$, which is exactly the shadowing region of the nuclear parton distribution function. This region dominates the integration for both $Q = 1$ GeV and $Q = 2$ GeV for $y = 2$. Our calculation for the rapidity distribution of the total cross section shows that the cross section does not start to drop until $y \sim 3$. This indicates that the production rate in the forward region is not smaller than in the central region as long as $y \leqslant 3$. Therefore, low-mass Drell–Yan in the forward region is an excellent probe of the nuclear shadowing effect and may help us understand the suppression of hadron production in the forward region at RHIC.

In summary, low-mass Drell–Yan dilepton production is a potentially clean probe of small-x gluons, without strong final state interactions. When $Q_{\mathrm{T}} > 1$ GeV, the gluon-initiated sub-processes contribute more than 70% to the cross section. We have also shown that the forward region is very sensitive to small-x gluons. Unfortunately, low-mass Drell–Yan dilepton production suffers from low production rate at RHIC due to the Drell–Yan factor. At LHC energies, high-Q_{T} low-mass Drell–Yan production is an excellent probe of the gluon distributions.

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References

[1] Accardi A *et al* 2003 *Preprint* hep-ph/0308248
[2] Berger E L, Gordon L E and Klasen M 1998 *Phys. Rev.* D **58** 074012 (*Preprint* hep-ph/9803387)
[3] Berger E L and Qiu J-W 1990 *Phys. Lett.* B **248** 371
[4] Berger E L, Qiu J-W and Zhang X-F 2002 *Phys. Rev.* D **65** 034006 (*Preprint* hep-ph/0107309)
[5] Albajar C *et al* (UA1 Collaboration) 1988 *Phys. Lett.* B **209** 397